

Which type of planets do we expect to observe in the Habitable Zone?

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Abstract We used a sample of super-Earth-like planets detected by the Doppler spectroscopy and transit techniques to explore the dependence of orbital parameters of the planets on the metallicity of their host stars. We confirm the previous results (although still based on small samples of planets) that super-Earths orbiting around metal-rich stars are not observed to be as distant from their host stars as we observe their metal-poor counterparts to be. The orbits of these super-Earths with metal-rich hosts usually do not reach into the Habitable Zone (HZ), keeping them very hot and uninhabitable. We found that most of the known planets in the HZ are orbiting their GK-type hosts which are metal-poor. The metal-poor nature of planets in the HZ suggests a high Mg abundance relative to Si and high Si abundance relative to Fe. These results lead us to speculate that HZ planets might be more frequent in the ancient Galaxy and had compositions different from that of our Earth.

Keywords Planet composition · Stellar abundances · Habitability · Planetary orbits

1 Introduction

Twenty years ago, in 1995, the first extrasolar planet orbiting a main sequence solar-type star, 51 Pegasi, was detected (Mayor and Queloz, 1995). Nowadays, several thousand of exoplanets and exoplanet candidates are announced, dozens of them being located in the so called habitable zone: a zone where exoplanets permitted to have liquid water on their solid surface (Cruz and Coontz, 2013; Kopparapu et al, 2013). This large amount of discovered exoplanets allowed to achieve an unprecedented advancement on our understanding of formation and

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evolution of exoplanets, although, sometimes, newly discovered planets bring more questions than answers. The recorded progress was possible due to many observational studies of individual and statistical properties of exoplanets (and their host stars), successfully followed by theoretical explanations.

One of the first observed properties of exoplanets was the giant-planet occurrence dependence on the host star metallicity (e.g. Gonzalez, 1997; Santos et al, 2001, 2004; Johnson et al, 2010; Mortier et al, 2013). Interestingly, this dependence, if exist, is likely very weak for low-mass/small-size planets (e.g. Sousa et al, 2011; Buchhave and Latham, 2015). These observational results were theoretically explained within the context of core-accretion theory of planet formation (Ida and Lin, 2004; Mordasini et al, 2012). It is worth noting that these correlations were recently reproduced in the context of gravitational instability too. This was done by Nayakshin and Fletcher (2015), who used a Tidal Downsizing hypothesis for planet formation.

The importance of stellar (and disk) metallicity is probably not only limited to the formation of planets. Recently, it was shown that the architecture of planets may also depend on the stellar metallicity (Beaugé and Nesvorný, 2013; Dawson and Murray-Clay, 2013; Adibekyan et al, 2013). Moreover, Dawson et al (2015) proposed that the presence or absence of gaseous atmosphere of small-sized planets depends on metallicity thorough disk solid surface density.

In all the aforementioned studies, the iron content was used as a proxy for overall metallicity. However, recent works showed that elements other than iron may play a very important role for planet formation. In particular, it was shown that iron-poor stars hosting giant (Haywood, 2008, 2009; Adibekyan et al, 2012b) and low-mass (Adibekyan et al, 2012a) planets are systematically enhanced in α -elements. It was also shown that low-mass planet hosts show a high Mg/Si abundance ratio compared to the field stars without any detected planetary companion (Adibekyan et al, 2015).

The importance of individual heavy elements and specific elemental ratios is not only limited to the formation of the planets, but may also control the structure and composition of the planets (e.g. Grasset et al, 2009; Bond et al, 2010; Delgado Mena et al, 2010; Rogers and Seager, 2010; Thiabaud et al, 2014, 2015; Dorn et al, 2015; Kereszturi and Noack, 2016). In particular, Mg/Si and Fe/Si mineralogical ratios were proposed to allow to constrain the internal structure of terrestrial planets (Dorn et al, 2015). These theoretical models were recently successfully tested on three terrestrial planets by Santos et al (2015).

In this work we will first revisit the results of Beaugé and Nesvorný (2013) and Adibekyan et al (2013) on the dependence of orbital distance (a) of small-size/low-mass planets on metallicity. Then, by extrapolating our results, we discuss the possible properties of planets in the HZ.

2 Super-Earths on the period – mass/radius diagram

The recent works of Beaugé and Nesvorný (2013) and Adibekyan et al (2013) indicate that there is a dependence of orbital distances of super-Earths and Neptune-like planets on the stellar metallicity. Beaugé and Nesvorný (2013), by using a sample of exoplanet candidates from the *Kepler* mission, found that small planets ($R_p < 4R_\oplus$) orbiting around metal-poor stars always have periods greater than 5

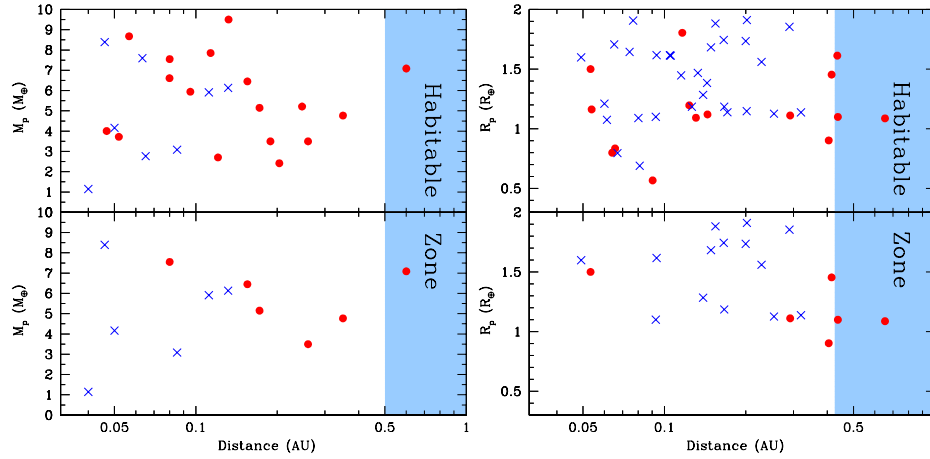


Fig. 1 The position of low-mass planets around FGK dwarf stars on the $a - M_p$ plane (left panel) and of small-size planets around FGK dwarf stars on the $a - R_p$ plane (right panel). The bottom panels show the position of the planets at the largest orbital distances in the systems. Red circles correspond to planets orbiting stars with $[\text{Fe}/\text{H}] \leq -0.1$ dex and blue crosses represent planets orbiting metal-rich stars with $[\text{Fe}/\text{H}] > -0.1$ dex. The HZ of the star with the shortest inner edge distance from the star is presented in blue shade.

days, while planets with similar sizes but around metal-rich stars show shorter periods. Adibekyan et al (2013), by using a sample of radial velocity (RV) detected exoplanets, found that low-mass planets around metal-rich stars do not show large orbital periods (greater than 20 days), while planets of the same mass, but orbiting around metal-poor stars span a wider range of orbital periods (see their Fig. 2). These two results are not fully compatible and may come from the possible detection biases in the RV or transit surveys, from the way how the samples were built, or from the low-number statistics. However, they both suggest that the period (or orbital distance) distribution of the observed planets depends on the stellar metallicity.

2.1 Distance – mass diagram for low-mass planets

To revisit the results of Adibekyan et al (2013), we selected all the RV detected low-mass planets (exoplanet.eu¹) around FGK dwarf stars ($M_* > 0.5M_\odot$) for which stellar parameters were derived in a homogeneous way (SWEET-Cat: Santos et al (2013))². Since, low-mass planets around metal-rich stars may have higher mass planetary companions at larger distances that may affect (due to gravitational interactions) the orbital distances of the planets (Adibekyan et al, 2013), we selected only those systems where the highest mass planetary companion has $M_p \leq 10M_\oplus$.

Our sample consists of 26 planets in 12 systems. On the top-left panel of Fig. 1 we show the position of all the planets on the $a - M_p$ diagram, separating planets by their host star’s metallicity. The bottom-left panel shows positions of the planets with the largest orbital distances in the system. The figure clearly hints a lack

¹ <http://exoplanet.eu/>

² <https://www.astro.up.pt/resources/sweet-cat>

of planets at large orbital distances from their metal-rich hosts and confirms the result of Adibekyan et al (2013).

To evaluate the statistical significance of this result we applied a simple binomial statistics test. All the RV detected planets orbiting around metal-rich stars (9 planets) are within 0.13 AU distance from their hosts (see the top-left panel of Fig. 1). There are also 9 planets orbiting around metal-poor stars within the same distance. Thus, if we assume that the metallicity is not the parameter that determines the positions of these planets in the plot, then the probability of a planet to orbit around a star within the mentioned distance is $(9+9)/26$ (26 is the total number of planets). Under this assumption our data follows the binomial distribution and the binomial statistics give a probability of $P_{bin}=0.039$ that all the planets orbiting metal-rich stars would orbit within 0.13 AU distance from their hosts by chance. The same statistical test when applied to the data from the bottom-left panel of Fig. 1 provide probability of $P_{bin}=0.036$.

A quite common test that could be performed to our data is the bootstrapping. If we shuffle the whole data large number of times and count the number of trials that all the planets around metal-rich stars have orbits closer than 0.13 AU we can calculate the probability that the event occurred by chance (see e.g. Adibekyan et al, 2013). However, these probability values will be very close to the p-values obtained from the binomial statistics, because the underlying assumption is the same.

We would like to stress that the samples are small, therefore, the results and conclusions regarding them should be considered with caution.

It is also very interesting to note that planets around metal-rich stars are usually in single or double systems, while metal-poor stars host more planets (up to six planets – HD40307: (Tuomi et al, 2013)).

2.2 Distance – radius diagram for small-size planets

We constructed our transit sample from that of Buchhave et al (2014), by selecting planetary systems that contains only small-size planets of $R_p \leq 2R_{\oplus}$ and orbiting around FGK dwarfs. We note that this radius is an approximate maximum radius for habitable planets as suggested by Alibert (2014). To decrease the possible false-positive rates in our sample, we selected only planets which are confirmed (NASA Exoplanet Archive³) or planets which are in multiple systems (see Lissauer et al, 2012). Following Buchhave et al (2014), we excluded systems with highly irradiated planets (stellar flux $F > 5 \times 10^5 \text{ J s}^{-1} \text{ m}^{-2}$), that might have undergone significant atmospheric evaporation (see also Owen and Wu, 2013). Our final sample consists of 45 planets in 20 systems.

The distributions of all the planets and the planets with the largest orbital distance in a system on the $a - R_p$ plane are shown on the top-right and bottom-right panels of Fig. 1. As for the RV detected planets, the planets are separated according to their host star metallicity. The distribution of the a of the transiting planets is qualitatively similar to that of RV detected planets. Planets around metal-rich stars do not orbit their stars at distances as large as their metal-poor counterparts. However, orbital distances of the metal-rich transiting planets are

³ NASA Exoplanet Archive – <http://exoplanetarchive.ipac.caltech.edu/>

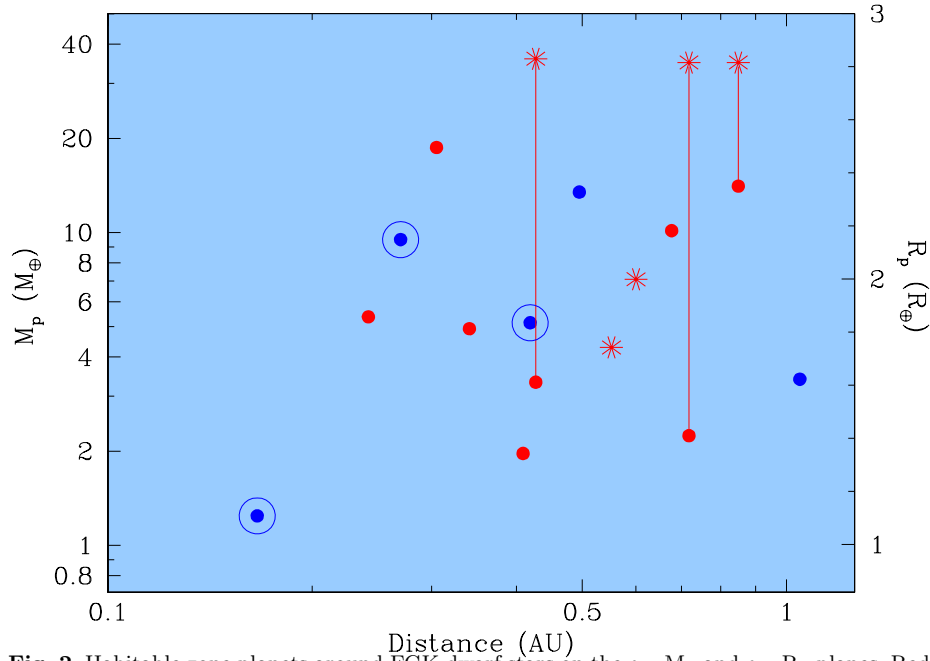


Fig. 2 Habitable zone planets around FGK dwarf stars on the $a - M_p$ and $a - R_p$ planes. Red symbols correspond to planets orbiting stars with $[\text{Fe}/\text{H}] \leq -0.1$ dex and blue symbols represent planets orbiting metal-rich stars with $[\text{Fe}/\text{H}] > -0.1$ dex. Planets with mass measurements are presented by asterisks and with radius measurements by filled circles. The three planets with both mass and radius measurements are connected by red lines. Three planets orbiting the coolest stars are marked by open large circles.

slightly larger than that observed for metal-rich planets detected with the Doppler spectroscopy.

We applied the same binomial statistics as it was done for the RV detected planets and obtained $P_{bin} = 0.029$ and $P_{bin} = 0.044$ for the samples of the top-right and bottom-right panels of Fig. 1, respectively. We again would like to remind the reader about the limited size of the samples.

It is interesting to see that the fraction of metal-poor planets is much lower in the transiting data than in the RV sample. This might be related to the different fields (e.g. different stellar populations) surveyed by the RV and transit search programs, and/or shift of the zero-points of the metallicities. However, Adibekyan et al (2012b) showed that there is a good agreement between metallicities derived by Buchhave et al (2012) and by standard spectroscopic techniques based on curve of growth (e.g. Sousa et al, 2008). It is also still possible that some of the transiting planet candidates are false positive that affects the true metallicity distribution of the transiting samples.

We note that Beaugé and Nesvorný (2013) did not find small planets around metal-poor stars with short orbital periods, likely because their sample was about one third of this sample.

2.3 Planets in the habitable zone

In Fig. 1, we show the HZ of the star with the shortest inner edge distance from the star. The HZ of the RV detected planet hosts are calculated following Kopparapu et al (2013). For the transiting planets it is hard to get precise information on the host stars luminosity, because of their poor distance estimation. In the right panel of the plot the HZ starts from $a=0.427$ AU, which is the orbital distance of Kepler-62e, a habitable planet around K type star (Borucki et al, 2013). As one can see, most of the planets orbit their stars in the zone where the temperature is still high for water to be in a liquid form at the surface of the planets. While the lack of long-distance super-Earths is mostly due to the detection limits in the planet search programs, this bias probably is not responsible for the sub-grouping of planets depending on their host stars metallicity. Fig. 1 shows that metal-poor super-Earths are closer to the HZ than their metal-rich counterparts, and the two planets (Kepler-62e and HD40307g), that are located in the HZ, are hosted by metal-poor stars.

In Fig. 2, we plot all the known planets in the HZ that are orbiting FGK type stars⁴ on the $a - M_p$ and $a - R_p$ planes. Ten out of the 15 planets (note, that three planets are plotted twice because they have both radius and mass measurements) are orbiting stars with $[\text{Fe}/\text{H}] < -0.1$ dex. In fact, all the five planets for which there is a RV confirmation are orbiting low-metallicity stars. Three of the planets orbiting metal-rich stars, have the coolest hosts in the sample with the $T_{\text{eff}} < 4050$ K, for which the derivation of stellar parameters, including metallicity is more difficult, hence probably less precise.

3 Concluding remarks and outlook

Our samples of low-mass and small-size planets detected by the RV and transit methods show that planetary architecture depends on the metallicity of the disk where they formed. In particular, we showed that these super-Earths orbiting around metal-rich stars ($[\text{Fe}/\text{H}] > -0.1$ dex) do not have orbits as large as it is observed for their metal-poor counterparts. The orbits of the super-Earths with metal-rich hosts, usually do not reach to the HZ, making them very hot and inhabitable. We note that the maximum mass and radius of the selected planets are $10M_{\oplus}$ and $2R_{\oplus}$, which are approximate limits for habitable planets (Alibert, 2014).

The sample of 15 planets orbiting their FGK hosts inside the HZ (all the known planets), shows that these planets tend to orbit stars with low metallicities: only three out of the 15 planets have hosts with metallicity higher than that of the Sun. The only planet in the HZ orbiting solar-like (G-type) metal-rich star is the very recently discovered Kepler-452b (Jenkins et al, 2015).

The extrapolation of our results, that the planets in the HZ tend to orbit around metal-poor stars, can have very interesting and important implications. As it was shown in Adibekyan et al (2012b), metal-poor hosts of super-Earths tend to be enhanced in α -elements, which means high Si/Fe ratio. Similarly, metal-poor low-mass planet hosts are more enhanced in Mg relative to Si, i.e. high

⁴ <http://phl.upr.edu/projects/habitable-exoplanets-catalog>

Mg/Si ratio (Adibekyan et al, 2015). These two mineralogical ratios, Si/Fe and Mg/Si, are very important for the formation of terrestrial planets (e.g. Bond et al, 2010; Dorn et al, 2015). Moreover, the structure and composition of the planets is controlled by these ratios (Dorn et al, 2015).

The discussion presented above, on the dependence of composition of planets on the chemical properties of their hosts, leads us to speculate that probably the frequency of planets in the HZ was higher in the ancient Galaxy and in the outer disk of the Galaxy, when/where the metallicity is on average lower than in the solar neighborhood. Moreover, most of these planets in the HZ (because of lower metallicity, high Si/Fe, and high Mg/Si) should have composition that might be very different than that of our Earth.

Our results and discussion is based on a small sample of low-mass/small-size planets and some of the conclusions are, of course, very speculative. We have an example of our Earth – a habitable planet in the HZ – which is orbiting a non-metal-poor star. The future large planet search missions, such as TESS, CHEOPS, and PLATO-2.0 will certainly help us to make the picture more clear and to understand if the case of the Earth is a rule or rather an exception.

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